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Effect of sensor quantity on measurement accuracy of log inner defects by using stress wave

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Abstract: Wood nondestructive testing (NDT) is one of the high efficient methods in utilizing wood. This paper explained the principle of log defect testing by using stress wave, and analyzed the effects of sensor quantity on defect testing results by using stress wave in terms of image fitting degree and error rate. The results showed that for logs with diameter ranging from 20 to 40 cm, at least 12 sensors were needed to meet the requirement which ensure a high testing accuracy of roughly 90% of fitness with 0.1 of error rate. And 10 sensors were recommended to judge the possible locations of defects and 6 sensors were sufficient to decide whether there were defects or not.

Keywords: Sensor quantity; Log defect testing; Stress wave; Image fitting degree

Introduction

Quality assessment and defects detection of woods had the important effects on forestry industry. Nondestructive evaluation on the properties of logs is necessary to solve practical problems without the destruction of the integrity of trees (Yang *et al*. 2005b). The earliest method was to take an increment core from the trees, which was considered nondestructive for its life and to develop different nondestructive techniques for studying main physical characteristics of trees.

Researchers have used a number of techniques to investigate the detection of defects in wood. Conners *et al*. (1983) used a thresholding technique to locate surface defects on gray-scale images of hardwood lumber. Butler *et al*. (1989) reported that the use of RGB color information increased pixel-based defect detection accuracy for some subtle defects by over 20 percentage points compared to gray-scale accuracy. Sobey and Semple (1989) used the Conners *et al*. (1983, 1984) gray-scale approach on radiata pine (*Pinus radiata*) lumber, but the measures were calculated for larger local areas of fixed size and only included mean, variance, and kurtosis. They reported an overall defect detection accuracy of 95% but clear wood accuracies of only 75%−80%. Sobey *et al.* (1989) then followed up that study with a neural network-based classifier, but only overall classification rates were given.

With the development of wood nondestructive testing technology, stress wave technology is widely used in fields of wood industry due to its lower cost in comparison with other technologies including CT and x-rays, etc. In recent years, stress wave technology has been used to test wood defect with stress wave sensors simultaneously (Wang *et al*. 2002). This paper studied the effects of sensor quantity on the fitness and error of testing images by using stress wave.

Principle of log defect testing by using stress wave

The general principle is that a sensor is flipped to produce a stress wave propagated in wood and received by other sensors. The time interval in the process is recorded to calculate the propagation speed of stress wave between two sensors. Stress wave propagation in log is a dynamic process that is directly related to the physical and mechanical properties of log. Generally, wave propagates more rapid in high density hard wood and slower in low density soft wood (Yang *et al*. 2005a). By measuring wave transmission time in the radial direction, the internal condition of the log can be fairly accurately evaluated. This measured time can be used as a predictor of the physical conditions inside the log when it is converted to wave speed (Lin *et al*. 2005).

Experiment methods

Experiment hypotheses

Ten logs in four tree species with two kinds of defects collected from Dailing Forestry Bureau, Heilongjiang Province were investigated in this study. The circumference of log disc is supposed to be a whole circle. All kinds of log defects are supposed to be normal geometric shape. Hollow is a normal circle, and crack is a triangle or rectangle.

Experiment conditions

Testing work was carried out inside laboratory at temperature of 20 °C and humidity of 72%.

Stress wave testing apparatus, Arbotom, was imported from Germany, and ST-85 digital apparatus of measuring log humidity,

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and computer were employed in the testing.

The whole log with natural defects is earmarked in number 1, number 2, until to number 10 (Table 1).

Table 1. The general characters of ten log samples

Serial number	Assortments	Log moisture content (%)	Log disc diameter (cm)	Defect category	Defect area (cm^2)
No.1	Aspen	8.5	36.8	Hollow	122.66
No.2	Aspen	8.6	33.74	Hollow	153.86
No.3	Birch	18.3	38.83	Hollow	196
No.4	Birch	17.5	30.24	Cracks	75.63
No.5	Aspen	9.3	31.96	Cracks	34
No.6	Korean Pine	15.5	31.19	Cracks	30.63
No.7	Korean Pine	13.5	21.96	Cracks	28
No.8	Korean Pine	13.3	31.83	Cracks	26.02
No.9	Ash	10.5	35.82	Hollow and Cracks	104.25
No.10	Ash	10.5	39.79	Hollow and Cracks	314

Experiment process

The tested log stands at one place where it is 1 or 2 meters away from computer and Arbotom testing apparatus. The pins are put into the circumference of log and kept on one level. Sensors are hanged on the pins orderly keeping sensors and pins perpendicular (to the horizontal plane). The arcs between the pins are measured and recorded.

The apparatus are connected, and the work state must be normal. Detailed connecting methods are omitted.

Small hammer is used to hit the shock bolt of each sensor about 8 to 10 times for reducing the random error. The data are observed and the error data should be deleted. Then the sensors with error data are hit again until error rate of all data under 3%. Meanwhile line graph and surface graph originate from Arbotom testing apparatus are analyzed.

The sensors are removed from the log, the pins are fixed again and sensor quantity is changed. This experiment is repeated until to end.

Experiment results

Surface graph

The testing log images of No.9 (Fig. 1) are taken as example to describe the experiment process. These images are tested by Arbotom software in different sensors, and intensified by Photoshop software.

Fig. 1 Cross section picture of log sample No. 9

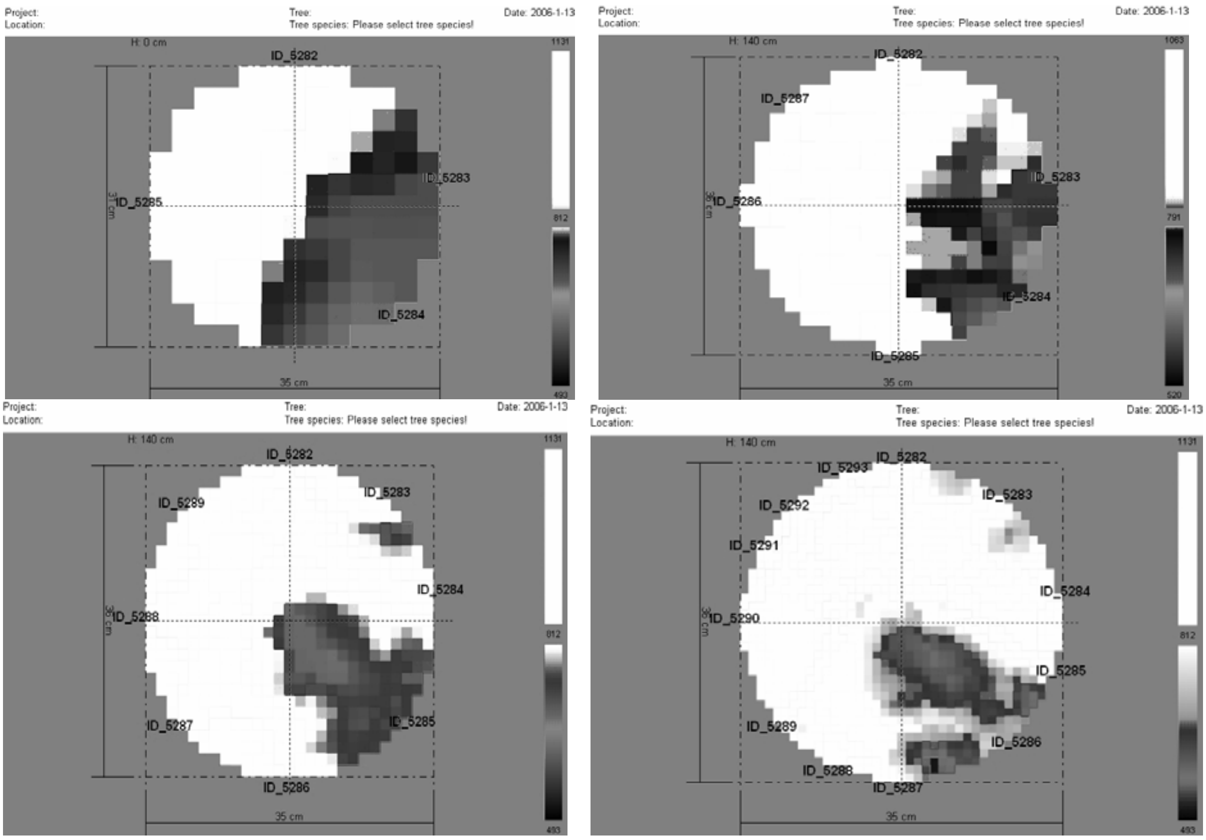

Fig. 2 The surface graph of log sample No. 9 with 4, 6, 8, 12 sensors respectively

In Fig. 2, the dark color areas are defect areas. It is clear that area and location of the tested defects approach actual defects gradually with sensor quantity increasing.

Experiment data

The size of graph, i.e. the length of graph (L) and the width of graph (W) can be shown from the graph originated from Arbotom. If the size of graph is known, the defected area tested could be calculated. The calculate steps are:

(1) The single grid area is calculated by using the length of graph (L) and the width of graph (W).

(2) The number of grids of defects is counted for N.

(3) The tested defect area is calculated by multiplying single grid area and defect grid number N (Table 2).

Table 2. Tested defect area of ten log samples cm^2

No.	Area	Sensor quantity						
		3	4	5	6	8	10	12
No.1	S_d	3.98	6.08	6.08	5.43	6.08	5.75	6.08
	N	51	35	31	28	24	26	21
	S_t	202.98	212.8	188.48	152.04	145.92	149.5	127.68
No.2	S_d	4.46	6.84	6.84	5.83	6.84	6.44	6.84
	N	50	34	32	33	30	27	25
	S_t	223	232.56	218.88	192.39	205.2	173.88	171
No.3	S_d	4.38	6.76	5.76	5.89	6.41	6.41	6.76
	N	64	60	54	51	40	34	31
	S_t	280.46	405.2	310.8	300.56	256.4	218.05	209.56
No.4	S_d	4.94	4.00	3.48	3.6	4	4	4
	N	43	35	34	27	25	22	19
	S_t	212.5	140	118.32	97.2	100	88	76
No. 5	S_d	5.70	4.40	4.13	4.13	4.27	4.41	4.27
	N	42	50	19	14	22	9	8
	S_t	239.50	220.44	78.47	57.82	93.94	39.69	34.16
No.6	S_d	4.00	5.69	5.15	5.14	5.50	5.50	5.69
	N	41	26	25	26	15	9	6
	S_t	163.76	147.85	128.70	133.54	82.54	49.53	34.12
No.7	S_d	3.99	5.98	5.19	5.16	5.98	5.70	5.98
	N	33	18	15	15	11	7	5
	S_t	131.59	107.56	77.78	77.41	65.78	39.92	29.88
No.8	S_d	4.15	6.06	5.15	5.68	5.68	5.68	6.06
	N	29	17	17	12	9	8	5
	S_t	120.46	103.01	87.51	68.17	51.12	45.44	30.29
No.9	S_d	6.9	5.76	4.84	4.96	5.76	5.44	5.76
	N	50	50	42	31	27	23	19
	S_t	345	288	203.09	153.76	155.52	125.12	109.44
No.10	S_d	4.67	7.11	6.08	6.22	6.22	6.76	7.11
	N	93	78	57	58	54	50	46
	S_t	434	554.67	346.56	360.89	336	337.78	327.11

Notes: N is the number of defect grids. S_d is single grid area and S_t is the tested defect area.

From Table 2, the number of defect grid drops with sensor quantity increasing, and the tested defect area also reduces gradually, which approaches the actual defect of samples gradually as a result. While closing to the actual defect, the tested defect area becomes smaller. But there are some data that do not conform to this rule. Because the defects of samples are very complex, there are errors during the experiment.

Analysis of experiment results

Image fitting degree and error rate

For analyzing the effects of sensor quantity on the measurement accuracy of log defects, stress wave is used by setting two indexes: image fitting degree and error rate (Yang *et al*. 2002). Image fitting degree reflects the degree of image matching by using the ratio of actual defect area to tested defect area. S_z is actual defect area, S_t is tested defect area, T is image fitting degree. There is

$$T = \frac{S_z}{S_t} \times 100\ \% \tag{1}$$

Error rate reflects the deviation degree of actual defect area to tested defect area. V is error rate. The math formula is

$$V = \frac{\left|S_t - S_z\right|}{S_z} \tag{2}$$

From above two formulas, accuracy of stress wave testing is higher when image fitting degree approaches 100% and error rate approaches 0.

Effects of sensor quantity on image fitting degree and error rate

Image fitting degree and error rate of ten samples are calculated according to the defects area and the equation (Table 3).

The image fitting degree approaches 100% and error rate ap-

proaches 0 gradually with sensor quantity increasing (Table 3). The accuracy of stress wave testing for log defect also increases gradually with sensor quantity increasing.

Table 3. The image fitting degree and the error rate of ten samples in different sensor quantity

No.	Area	Sensor quantity 3	4	5	6	8	10	12
No.1	S_t	202.98	212.8	188.48	152.04	145.92	149.5	127.68
	S_z	122.66	122.66	122.66	122.66	122.66	122.66	122.66
	T_1	60%	57%	65%	81%	84%	82%	96%
	V_1	0.65	0.73	0.53	0.24	0.19	0.22	0.04
No.2	S_t	223	232.56	218.88	192.39	205.2	173.88	171
	S_z	153.86	153.86	153.86	153.86	153.86	153.86	153.86
	T_2	69%	66%	70%	79%	75%	88%	90%
	V_2	0.45	0.51	0.42	0.25	0.33	0.13	0.11
No.3	S_t	280.46	405.2	310.8	300.56	256.4	218.05	209.56
	S_z	196	196	196	196	196	196	196
	T_3	70%	48%	63%	65%	76%	90%	94%
	V_3	0.43	1.07	0.59	0.53	0.31	0.11	0.07
No.4	S_t	212.5	140	118.32	97.2	100	88	76
	S_z	75.625	75.625	75.625	75.625	75.625	75.625	75.625
	T_4	36%	54%	64%	77%	76%	86%	99%
	V_4	1.81	0.85	0.56	0.29	0.32	0.16	0.005
No.5	S_t	239.50	220.44	78.47	57.82	93.94	39.69	34.16
	S_z	34	34	34	34	34	34	34
	T_5	14%	15%	43%	59%	36%	86%	99%
	V_5	6.04	5.48	1.30	0.70	1.76	0.16	0.005
No.6	S_t	163.76	147.85	128.70	133.54	82.54	49.53	34.12
	S_z	30.63	30.63	30.63	30.63	30.63	30.63	30.63
	T_6	19%	21%	24%	23%	37%	62%	90%
	V_6	4.35	3.83	3.20	3.36	1.69	0.62	0.11
No.7	S_t	131.59	107.56	77.78	77.41	65.78	39.92	29.88
	S_z	28	28	28	28	28	28	28
	T_7	21%	26%	36%	36%	43%	70%	94%
	V_7	3.69	2.84	1.78	1.76	1.35	0.425	0.07
No.8	S_t	120.46	103.01	87.51	68.17	51.12	45.44	30.29
	S_z	26.02	26.02	26.02	26.02	26.02	26.02	26.02
	T_8	22%	25%	30%	38%	51%	57%	86%
	V_8	3.63	2.95	2.36	1.62	0.96	0.75	0.16
No.9	S_t	345	288	203.09	153.76	155.52	125.12	109.44
	S_z	104.25	104.25	104.25	104.25	104.25	104.25	104.25
	T_9	30%	36%	51%	68%	67%	83%	95%
	V_9	2.31	1.76	0.94	0.47	0.49	0.20	0.05
No.10	S_t	434	554.67	346.56	360.89	336	337.78	327.11
	S_z	314	314	314	314	314	314	314
	T_{10}	72%	57%	91%	87%	93%	93%	96%
	V_{10}	0.38	0.77	0.10	0.15	0.07	0.07	0.04

Regression analysis

Calculation on average image fitting degree and average error rate

For reducing error, the average values of image fitting degree and error rate of ten samples are used as final value, and then the relationships between them are analyzed by SPSS software.

From Table 4 and Fig.3, for logs with diameter ranging from 20 to 40 cm, at least 12 sensors were needed to meet the requirement which ensure a high testing accuracy of roughly 90% of fitness with 0.1 of error rate. And 10 sensors are recommended to judge the possible locations of defects and 6 sensors are sufficient to decide whether there are defects or not.

Table 4. Average image fitting degree and average error rate with different sensor quantity

Item	Sensor quantity 3	4	5	6	8	10	12
T	41.3%	40.5%	53.7%	61.3%	63.8%	79.7%	93.9%
V	2.374	2.079	1.178	0.937	0.747	0.285	0.066

Regression analysis by using SPSS software

SPSS softwares were used to conduct the regression analysis between sensor quantity and image fitting degree or error rate

and the analysis results are shown as following:

The correlation coefficient (R) between image fitting degree and sensor quantity is 0.983, and the regression equation is

$$y = 0.22 + 0.058x, \quad x = \{3, 4, \cdots, 12\} \tag{3}$$

where, y is the image fitting degree and x is the sensor quantity. The correlation coefficient (R) between error rate and sensor quantity is 0.939, and the regression equation is

$$y = 2.787 - 0.247x, \quad x = \{3, 4, \cdots, 12\} \tag{4}$$

where, y is the error rate and x is the sensor quantity. The image fitting degree and error rate between actual defect and tested defect with different sensor quantity are estimated by the regression equation.

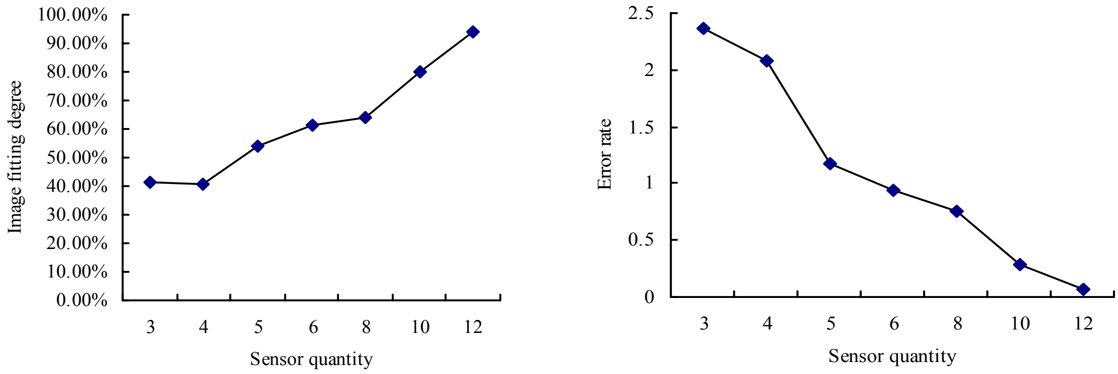

Fig. 3 The relation between sensor quantity and average image fitting degree or average error rate

Conclusions

The correlation between sensor quantity and image fitting degree is positive and notable. The regression equation between them is $y = 0.22 + 0.058x, \quad x = \{3, 4, \cdots, 12\}$.

The correlation between sensor quantity and error rate is negative and notable. The regression equation between them is $y = 2.787 - 0.247x, \quad x = \{3, 4, \cdots, 12\}$.

For logs with diameter ranging from 20 to 40cm, at least 12 sensors were needed to meet the requirement which ensure a high testing accuracy of roughly 90% of fitness with 0.1 of error rate. And 10 sensors are recommended to judge the possible locations of defects and 6 sensors are sufficient to decide whether there are defects or not.

Sensor quantity has great effects on the precision of log defects testing by using stress wave. Appropriately increasing sensor quantity can enhance image fitting degree and reduce error rate, and finally enhance the precision of stress wave testing. However, it is not enough to enhance the precision of stress wave testing by increasing sensor quantity. Because it is influenced by various factors, for example power of hitting the shock bolt using small hammer, position of sensor on the level, various assortments, percentage of moisture and density etc. Therefore further research work should be beneficial on testing the log inner defects by using stress wave.

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